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14. ABSTRACT
This project is to investigate and verify the feasibility for development of a methodological approach and corresponding tools for the management of intelligence, surveillance, and reconnaissance (ISR) systems. Our focus is on problem classes for which fast heuristics may be developed for both the construction of feasible solutions and for the improvement of such solutions. However, rather than considering heuristics in isolation, we wish to obtain maximum benefit from their availability by employing them within partition-based strategies. This research is built on the very recent research in the area of computational intelligence. The newly developed methodology, the Nested Partitions (NP) framework has its ability to incorporate feasibility heuristics (in which a number of good quality feasible solutions are generated via problem-specific techniques) as well as general search heuristics such as Tabu Search (TS), Greedy Search (GS), and Genetic Algorithms (GA's).

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An Optimization Framework For Intelligence, Surveillance, and Reconnaissance Systems

Final Report

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Grant Number: FA9550-04-1-0179

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1. Summary

This project is to investigate and verify the feasibility for development of a methodological approach and corresponding tools for the management of intelligence, surveillance, and reconnaissance (ISR) systems. Our focus is on problem classes for which fast heuristics may be developed for both the construction of feasible solutions and for the improvement of such solutions. However, rather than considering heuristics in isolation, we wish to obtain maximum benefit from their availability by employing them within partition-based strategies. This research is built on the very recent research in the area of computational intelligence. The newly developed methodology, the Nested Partitions (NP) framework has its ability to incorporate feasibility heuristics (in which a number of good quality feasible solutions are generated via problem-specific techniques) as well as general search heuristics such as Tabu Search (TS), Greedy Search (GS), and Genetic Algorithms (GA's). Numerical results show that the hybrid algorithms resulting from the combination of NP framework with high-performance heuristics not only significantly outperform branch-and-bound, but are also more robust and efficient than the pure search heuristics alone.

2. Objectives

- Contribute to the effective management of intelligence, surveillance, and reconnaissance systems by providing automated tools that can aid mission-critical decision-making.
- Bring innovative perspectives and insights from other problem domains to an important application area with great potentials.
- Develop new fast optimization and approximation algorithms for solving large-scale, real-time military problems such as clustered objects tracking problems and scheduling problems.
- Investigate alterative models and formulations that are more robust and scalable than conventional ones.
- Accumulate valuable computational experience with difficult problem instances and provide guidelines for successful system implementations.

3. Status of Effort:

We have worked on the development of methodologies for solving a variety of combinatorial optimization problems that include scheduling and planning problems, network design problems, and healthcare delivery problems. We developed the Generalized Dynamic Programming approaches for solving difficult planning and scheduling problems. We also develop effective lower bound for solving difficult scheduling problems. Our research results are summarized in the next section.

4. Accomplishments/New Findings:

Our research results can be summarized in the following:

1. Finding the best root node strategy for the approximation of the time-indexed bound in min-sum scheduling. (submitted to *OR letters*)
We identify the best root node strategy for the approximation of the time-indexed bound in min-sum scheduling by sorting through various options that involve the primal simplex, dual simplex, and barrier methods for linear programming, the network simplex method for network flow problems, and Dantzig-Wolfe decomposition and column generation.

2. A New Optimization Approach to the General Single Machine Earliness-Tardiness Problem. (Submitted to *IEEE Trans. on Automation Science and Engineering*). In this paper, we consider the single-machine earliness-tardiness (E-T) scheduling problem with distinct release dates, due dates, and E-T costs. The problem is formulated using dynamic programming. The solution procedure embodies a new hybrid optimization approach called generalized dynamic programming (GDP), which incorporates techniques from all three methodologies: dynamic programming, branch-and-bound, and dichotomy. An assignmentbased lower bound is employed in branch-and-bound. We test 135 random instances with up to 30 jobs to evaluate the algorithm's performance. It shows that the GDP approach achieves much better results than linear programming-based branch-and-bound algorithms such as those included in the commercial package, CPLEX.

2. Generalized Dynamic Programming: A Unified Optimization Framework: (to appear in *IEEE Trans. on Automation Science and Engineering*). Dynamic programming, branch-and-bound, and constraint programming are the standard solution principles for obtaining optimal solutions of combinatorial optimization problems. We propose a new optimization framework called generalized dynamic programming, which integrates all these three methodologies. The unified framework leads to powerful solution procedures and enables us to better understand the computational complexity of individual problem instances. We demonstrate our approach through the optimal solution of the single-machine scheduling problem with the objective to minimize the total weighted completion time subject to release date constraints, which is known to be strongly NP-hard. Extensive computational experiments indicate that algorithms developed under the framework use orders of magnitude less storage than dynamic programming, and yet can still reap the full benefit of the dynamic programming property inherent in the problem. We are able to solve to optimality all 1,900 instances with up to 200 jobs, whereas the state-of-the-art algorithm can only handle 50-job instances effectively. We believe that generalized dynamic programming provides a powerful new alternative to the norm of algorithm construction in combinatorial optimization.

4. On the equivalence of max-min transportation lower bound and time-indexed lower bound (to appear in *Math Programming*) The paper deals with

scheduling/sequencing problems with min-sum objectives and general cost functions. We discretize the time horizon and construct transportation problems for lower bounding purposes. We present two main results. First, we show that the optimal adjustment of transportation costs to obtain the tightest possible lower bounds can be computed as a linear program, thereby eliminating the need to resort to expensive tools such as projectional subgradient optimization. Second, we prove that the optimal lower bound is in fact equal to the well-known time-indexed lower bound - a rather unexpected result. Our results provide an alternative to the computation of the time-index lower bound.

5. NESTED PARTITIONS BASED COLUMN GENERATION (to be submitted) Direct application of general-purpose branch-and-cut (BC) commercial solvers such as CPLEX to large-scale combinatorial optimization problems generally results in large optimization gaps. Structure-based techniques such as iterative Lagrangian-based methods that have generally been regarded as the most effective lower bounding procedures often require significant time to generate reasonable bounds. In this paper, we present a Column Generation algorithm for generating lower bounds that takes advantage of high-quality feasible solutions produced by Nested Partitions (NP). We demonstrate our approach by applying it to a set of multicommodity distribution system design problems. The results show that our approach is capable of efficiently producing very high quality feasible solutions and lower bounds. For large-scale problems in this class, this approach is significantly faster and generates better feasible solutions and lower bounds than either CPLEX (applied directly to the given MIP) or the iterative Lagrangian-based methods. We also briefly discuss some other large-scale MIP problem classes for which this approach is expected to be very effective.

6. Difference Matrix Metaheuristic for IMRT Intensity Map Segmentation (to appear in *Medical Physics*): At an intermediate stage of radiation treatment planning for IMRT, most commercial treatment planning systems for IMRT generate intensity maps that describe the grid of beamlet intensities for each beam angle. Intensity map segmentation of the matrix of individual beamlet intensities into a set of MLC apertures and corresponding intensities is then required in order to produce an actual radiation delivery plan for clinical use. Mathematically, this is a very difficult combinatorial optimization problem, especially when mechanical limitations of the MLC lead to many constraints on aperture shape, and setup times for apertures make the number of apertures an important factor in overall treatment time. We have developed, implemented, and tested on clinical cases a metaheuristic (that is, a method that provides a framework to guide the repeated application of another heuristic) that efficiently generates very high-quality (low aperture number) segmentations. Our computational results demonstrate that the number of beam apertures and beam-on time in the treatment plans resulting from our approach is significantly smaller than the corresponding values for treatment plans generated by the heuristics embedded in a widely-used commercial system. We also contrast the excellent results of our fast and robust

metaheuristic with results from an exact method, branch-and-cut, which attempts to construct optimal solutions, but, within clinically acceptable time limits, generally fails to produce good solutions, especially for intensity maps with more than five intensity levels. Finally, we show that in no instance is there a clinically significant change of quality associated with our more efficient plans.

5. Personnel Supported:

Dr. Leyuan Shi, Principal Investigator
Dr. Yunpen Pan, post-doc fellow.
Dr. Peng Chen, research associate
Dr. Bex, Thomas
Dr. Hoksung Yau
Weiwei Chen, Graduate student
Liang Pi, Graduate student
Tao Wu, Graduate student

6. Publications:

1. Shi. L. and Y. Pan, "New Hybrid Optimization Algorithms for Machine Scheduling Problems ," IEEE Trans. on Automation Science and Engineering (accepted).
2. Pan, Y. and Shi, L., On the Equivalence of Max-Min Transportation Lower Bound and Time-Indexed Lower Bound," Math Programming (accepted).
3. Gunawardena, A.D.A., D'Souza, W., L. Goadrich, K. J. Sorensen, R.R. Meyer, S. A. Naqvi, and L. Shi, "A Difference-Matrix Metaheuristic for Intensity Map Segmentation in Step-and-Shoot IMRT Delivery," Physics in Medicine and Biology. Vol.51, pp2517-2536, 2006
4. Shi, L. and Y. Pan, "Branch-and-bound algorithms for solving hard instances of the one-machine sequencing problem," European Journal of Operational Research Vol. 168. 3, pp1030-1039, 2006.
5. Pan, Y. and L. Shi, "Dual Constrained Single Machine Sequencing to Minimize Total Weighted Completion Time," IEEE Trans. on Automation Science and Engineering, Vol. 2. 4, pp. 344-357, 2005.
6. Nembhard, H. B., Shi, L. and M. Aktan "The Effect of Implementation Time Lag on Real Options Valuation," IIE Trans, Vol. 37. 10, pp 945-956, 2005.
7. Shi, L. and Y. Pan, "An Effective Technique for Enhancing Local Search Methods for the Job-Shop Problem," IEEE Trans. on Automation Science and Engineering. Vol. 2, pp. 73-77, 2005.
8. Liang, H., Bai, F. and L. Shi "Optimize the Partition of Variables in Multi-homogeneous Homotopy Methods", Applied Mathematics and Computation. Vol. 163, pp. 825-840, 2005.

9. Shi, L. B. Meyer, M. Bozbay, and A. Miller, "Large-Scale Supply Chain Network Optimization Via a Nested Partitions Framework", Journal of Systems Science and Systems Engineering, Vol. 13, pp. 158-179, 2004.
10. D'Souza, W., R.R. Meyer, and L. Shi, "Selection of Beam Orientations in Intensive-modulated Radiation Therapy Using Single-Beam Indices and Integer-programming," Physics in Medicine and Biology, Vol. 49, pp. 3465-3481, 2004.

7. Interactions/Transitions:

a. Participation/presentations at meetings, conferences,seminars, etc.

1. *"Recent Advances in Solution of Large-scale Optimization Problems"*, Boston University, September 2004.

2. *"Scheduling Issues in Manufacturing Enterprise Systems,"* INFROMS, Denver, October 2004.

3. Invited talk *"Nested Partitions Methods and Its Application in Information Technology,"* Xian University, October 2005.

4. *"On the Optimal Solution of the General Min-Max Sequencing Problem,"* Proceedings of the 2002 Winter Simulation Conference" Washington, D.C. 2004.

5. *"A STOCHASTIC ON-LINE MODEL FOR SHIPMENT DATE QUOTING WITH ON-TIME DELIVERY GUARANTEES,"* 2004 IEEE Conference on Decision and Control, Nassau, Bahamas. Dec. 2004, pp 1785-1792.

6. *"A New Optimization Approach to the General Single Machine Earliness-Tardiness Problem,"* 2005 IEEE Conference on Automation Science and Engineering, Edmonton, Canada. August. 2005.

7. *Recent Advances in Solution of Large-scale Optimization Problems"*, Penn State University, February 2006.

8. *Recent Advances in Solution of Large-scale Optimization Problems"*, IBM, March 2006

9. *"Nested Partitions Methods and Its Application in Information Technology,"* Exxsonmobil, NJ, April 2006.

10. "*A New Optimization Approach to the General Single Machine Earliness-Tardiness Problem*," 2005 IEEE Conference on Service Engineering, Shanghai, China. June 2006.

b. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories.

Panel reviewer for *National Science Foundation.*

Reviewer for Army Research Office

8. New discoveries, inventions, or patent disclosures. (If none, report None.)
Provisional Patent on Automated Radiation Treatment Planning, February 2007